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Annex A. Comparative Analysis Between the Proposed Rupture Forecasting Model and Current Operational Models

This annex compares the proposed crustal deformation and log-log convergence model against current operational approaches used in earthquakes and volcanic unrest, highlights the benefits of integrating the model with those approaches, and summarizes the comparative implications for short-term forecasting. The analysis focuses on the principal model families currently in use: earthquake early warning (EEW), probabilistic seismic hazard analysis (PSHA), operational earthquake forecasting (OEF), and failure-forecast approaches for volcanic unrest such as FFM and LPPLS. [web:262][web:264][web:265][web:266][web:273]

1. Comparative positioning of the model

The proposed model occupies a distinct position between post-initiation warning and long-term probability assessment. EEW is designed to issue alerts after an earthquake has already started, using rapid detection of the first seismic waves to estimate expected shaking with lead times typically measured in seconds. By contrast, PSHA describes long-term exceedance probabilities over years to decades and is not intended to resolve a specific short-term rupture time. [web:262][web:264][web:269]

Operational earthquake forecasting stands between those two layers by updating short-term probabilities based on recent seismicity, commonly through statistical models such as ETAS or related clustering approaches. These systems provide time-dependent hazard information, but current OEF frameworks generally do not identify a deterministic candidate rupture time and still struggle to assign high probabilities to future large earthquakes. The proposed model differs by introducing an explicit precursor-based critical-time estimator grounded in deformation dynamics and multivariable convergence logic. [web:265][web:266][web:268][file:242]

In volcanic settings, the nearest conceptual analogues are the Failure Forecast Method and more recent LPPLS-based eruption forecasting. FFM uses accelerating precursor behavior to estimate time to failure, while LPPLS extends that logic by incorporating non-monotonic or oscillatory structure that can improve fit to rupture dynamics in heterogeneous systems. The proposed model is compatible with that

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family of critical-transition methods but extends it by combining a normalized multivariable precursor index with an explicit integration pathway across tectonic and volcanic observables.
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2. Comparative table

Model family	Main purpose	Typical time horizon	Main data basis	Strengths	Main limitations	Relation to the proposed model
Earthquake Early Warning (EEW)	Rapid warning after rupture initiation	Seconds [web:262][web:264]	Real-time seismic wave detection [web:264]	Operationally mature, life-saving for immediate response [web:264]	Does not forecast before rupture begins [web:262][web:264]	The proposed model complements EEW by operating before rupture rather than after initiation [web:262][file:242]
Probabilistic Seismic Hazard Analysis (PSHA)	Long-term hazard estimation	Years to decades [web:262][web:269]	Historical seismicity, fault models, ground-motion relations [web:269]	Strong for infrastructure planning and long-term policy [web:269]	Not intended to estimate a short-term critical rupture time [web:262][web:269]	The proposed model adds short-term dynamic monitoring to a long-term hazard framework [web:262][file:242]
Operational Earthquake Forecasting (OEF)	Time-dependent short-term probability updates	Hours to days to weeks [web:265][web:266]	Seismicity sequences, clustering, statistical aftershock models [web:265][web:268]	Useful for changing hazard states and civil-protection decisions [web:265][web:271]	Common models still struggle to forecast future large earthquakes with high probability [web:266]	The proposed model can enrich OEF by adding deformation-based precursor information and a candidate t_c estimate [web:266][file:242]

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Failure Forecast Method (FFM)	Failure-time estimation from accelerating precursors	Days to weeks in unrest or failure episodes [web:267]	Monotonic precursor acceleration [web:267]	Physically intuitive and widely used in volcano monitoring [web:267]	Less flexible for intermittent or oscillatory precursor structure [web:273]	The proposed model is compatible with FFM logic but supports multivariable integration beyond a single precursor channel [web:267][file:242]
LPPLS-based failure forecasting	Critical-time estimation with log-periodic structure	Days to weeks in accelerating systems [web:270][web:273]	Accelerating and oscillatory precursor signals [web:270][web:273]	Stronger fit in several rupture datasets, including volcanic unrest [web:273][web:276]	Requires careful fitting and high-quality temporal data [web:270][web:273]	The proposed model shares the same critical-transition logic and can serve as an operationalized multivariable front-end to LPPLS-type estimation [web:270][web:276][file:242]

3. Benefits of integration with current models

The strongest practical advantage of the proposed model is not that it replaces current systems, but that it connects them across time scales and data domains. When integrated with EEW, the proposed framework supplies a pre-rupture surveillance layer, while EEW supplies rapid post-initiation warning after failure has begun. Together, they form a more continuous chain from pre-event monitoring to immediate emergency response. [web:262][web:264][file:242]

When integrated with PSHA, the model adds dynamic short-term situational awareness to a long-term hazard framework. PSHA remains the appropriate tool for infrastructure design and return-period analysis, while the proposed model contributes transient state information based on current deformation and seismic behavior. This combination is especially valuable for civil protection because it links structural background hazard with evolving short-term instability. [web:269][file:242]

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When integrated with OEF, the model offers one of the clearest gains. OEF systems already quantify time-dependent hazard based on recent seismicity, but recent reviews emphasize that commonly used models still face difficulty in assigning high probabilities to future large earthquakes and that ongoing advances seek to incorporate physical processes, precursory signals, and high-resolution data. The proposed framework directly addresses that need by adding geodetic acceleration, auxiliary anomalies, and multivariable convergence to the forecasting process. [web:266][web:268][web:271][file:242]

In volcanic settings, integration with FFM and LPPLS is particularly promising. FFM contributes a physically intuitive time-to-failure structure, while LPPLS contributes improved treatment of oscillatory and non-monotonic precursor behavior. The proposed model broadens both by providing a normalized multivariable index that can ingest deformation, seismic, hydrothermal, and environmental observables in a unified architecture. [web:267][web:270][web:273][web:276][file:242]

4. Comparative interpretation

Relative to current models, the proposed framework is strongest in settings where dense observational coverage allows reliable estimation of deformation velocity, acceleration, and multivariable precursor synchronicity. Its distinct contribution is not merely another statistical forecast, but a physically interpretable transition model linking observable precursor acceleration to an estimated critical time. This gives it explanatory power that is often absent in purely statistical clustering models. [web:266][file:242]

Its main challenge is that it requires higher observational quality and stronger preprocessing discipline than models based only on seismic catalogs. For that reason, the proposed framework is best deployed as an integration layer in well-instrumented regions rather than as a universal replacement for lighter-weight probabilistic tools. [file:242][web:265][web:266]

5. Conclusions

The comparative analysis shows that the proposed model fills a meaningful methodological gap between long-term hazard assessment, short-term probability updating, and post-initiation warning. EEW remains indispensable for immediate alerts after rupture onset, PSHA remains indispensable for long-term hazard planning, and OEF remains indispensable for authoritative short-term probability updates. The proposed model adds value by introducing a deformation-anchored, multivariable pathway to candidate critical-time estimation before rupture. [web:262][web:265][web:266][file:242]

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Its greatest benefit emerges through integration. Combined with EEW, it extends the warning chain backward in time. Combined with PSHA, it links background hazard to transient instability. Combined with OEF, it enriches short-term forecasting with physical precursor information. Combined with FFM and LPPLS, it provides a broader operational architecture across earthquakes, volcanic unrest, and related accelerating-failure systems. [web:262][web:269][web:271][web:273][web:276][file:242]

For well-instrumented regions, this integrated approach offers the clearest strategic benefit: a multi-layered forecasting ecosystem in which statistical, physical, and operational models support one another rather than compete. [web:265][web:272][file:242]

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